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Multi-Parameter Dynamical Measuring System Using Fibre Bragg Grating Sensors for Industrial Hydraulic Piping

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Abstract:

Due to the risk of failure induced by vibration fatigue, performance testing and condition monitoring are important to hydraulic piping systems in some critical industries such as nuclear power, oil and gas, and aerospace. A multi-parameter dynamical measuring system using Fibre Bragg Grating (FBG) sensors is proposed to detect multiple physical parameters (strain, temperature, pressure, acceleration, etc.) in industrial hydraulic piping. This paper investigates the multi-parameter measuring principle of FBG and presents the framework of the proposed system. Multi-parameter dynamical measuring experiments on a hydraulic piping test platform were carried out to validate the system. Multiple parameters of the hydraulic piping were obtained and analysed in the time, frequency and modal domains. The results obtained by FBG sensors are in good agreement with those detected by the reference electrical and piezoelectric sensors. The proposed system was implemented to monitor the clamp looseness of the pipe. Experimental results indicate that the proposed system could be used for multi-parameter dynamical measurements and real-time condition monitoring of complex industrial hydraulic piping systems in harsh environments.

Keywords: Hydraulic piping; Fibre Bragg Grating (FBG); Measuring systems; Dynamical measurement

1. Introduction

Due to harsh service environments of high pressure, high temperature, and intense vibration, hydraulic piping systems can fail [1, 2]. This can cause catastrophic consequences in some critical industries such as nuclear power, oil and gas, and aerospace [3-5]. Multi-parameter dynamical measurement of hydraulic piping systems is needed for performance testing and real-time condition monitoring to prevent fatigue failure [6-9]. State-of-the-art multi-parameter dynamical measuring technology and systems with high accuracy, good environmental adaptability and low cost, and permitting easy integration and operation, are in high demand [10, 11]. However, traditional electrical/piezoelectric sensors (such as resistance strain gauges, thermocouples, piezoelectric accelerometers, and electric pressure transducers) and electronic instruments, and non-destructive evaluation methods (for example, ultrasonic, acoustic emission, radiography, magnetic particle, and magnetic flux), are not suited to harsh environments [12, 13]. In addition, many of these sensors or methods have the disadvantages to make them inappropriate for multi-parameter dynamical measurements. For instance, sensor networks are complex and expensive, installation and maintenance are difficult, and capabilities for distributed real-time measurement and long-distance sensing signal transmission are extremely limited [14, 15].

Fibre Bragg Grating (FBG) employs light as sensing signal and data transmission, giving advantages like small dimensions, light weight, multi-parameter measuring, immunity to electromagnetic interference and multiplexing capabilities as well as resistance to corrosion [16, 17]. In recent decades, FBG sensors have been extensively investigated and widely implemented in a variety of fields to measure different physical parameters such as strain, temperature, pressure, force, acceleration and flow rate [18-21].

FBG strain sensors were used for structural dynamical measurements of helicopter blades and fighter aircraft to obtain strain modal parameters by Siemens [22]. 780 FBG sensors were mounted on the wings of an ultra-light aerial vehicle to measure 2D strains and determine the deflected shape of the wings and their out-of-plane loading [23]. Measurement of vibration-induced strain in hydraulic system pipelines based on FBG sensors was investigated [24]. For high temperature applications, an improved metal-package FBG sensor was developed using regenerated FBG [25]. Distributed FBG strain measurements were implemented for real-time reconstruction of the deformed shape of cylindrical bodies [26]. Dynamical measurement of strain in a four-pole induction motor stator using FBG strain sensors installed inside was carried out for broken bar fault detection [27]. Twisted FBG sensors were utilised to measure the strain and temperature in the metal machining process, simultaneously [28]. An FBG sensor was utilized to detect the steel material defects of the pipe [29]. FBG based strain sensors were applied for the monitoring of pipeline leakage and corrosion to ensure the pipeline safety operation [30, 31].

For dynamical liquid pressure measurement, a diaphragm-type FBG sensor was developed using two bare FBGs, and a sensitivity of 157 pm/bar within a range from 0 to 10 bar was achieved [32]. For measurement of high pressures up to 1400 bar and a temperature of 290 ℃, FBG was fabricated in a specialty fibre by a femtosecond pulsed laser and a pressure sensitivity of 3.3 pm/bar was obtained [33]. A liquid level monitoring sensor using polymer optical FBG and silicone rubber diaphragm was reported [34]. A differential FBG pressure sensor using magnetic transfer was proposed with a sensitivity of 11.2 pm/kPa [35]. FBG pressure sensors were used for pipeline leak detection based on negative pressure waves [36].

An accelerometer incorporating dual FBGs and lantern shape metallic shells was studied with a sensitivity of 9.4 pm/g and a resonance frequency of 1175 Hz [37]. Using two symmetrical spring plates, a low frequency FBG accelerometer was developed with a sensitivity of 1067 pm/g in a range from 0.7 Hz to 20 Hz [38]. An FBG accelerometer based on a flexure hinge was designed with sensitivities of around 13.1 pm/g and 12.0 pm/g in X and Y directions, respectively [39]. A miniaturised FBG accelerometer was designed using a thin polyurethane cylindrical shell, and its sensitivity was 54 pm/g over a flat frequency response zone with a resonant frequency of 480 Hz [40].

To obtain fluid flow rate and direction, an FBG sensor based on a cantilever, was proposed and demonstrated [41]. FBGs were used to characterise the single and two-phase flows of liquid in pipes [42]. A temperature-compensated toroidal centripetal flowmeter using FBGs mounted on a curved fiberglass beam was proposed and demonstrated experimentally with a repeatability error of 4.6% [43]. A FBG-based mass flow meter was investigated for mass flow rate measurements with a sensitivity of

29 pm/(g.s^{-1}) [44]. To solve cross-sensitivity problems, two FBGs were employed in a small probe-type flowmeter with a measurement resolution of 0.81 m^3/h [45]. Using a core-offset FBG, a thermal gas flowmeter was demonstrated, and its detection limit was 0.178 m^3/h in a range up to 32 m^3/h [46].

Despite many applications of FBG sensors, multi-parameter dynamical measurement for hydraulic piping systems has not been much explored. Based on previous research results concerning pressure sensors [32, 47], dynamical strain measurement [24], strain modal analysis [48] and multi-parameter measurement [49], a new multi-parameter dynamic measuring system using FBG sensing is proposed for hydraulic piping to detect multiple parameters including strain, temperature, pressure and acceleration. Unlike the above cited work on sensor developments [32, 47] and measuring methods [24, 48], this paper focuses on measuring system integration. The system can accommodate numerous FBG sensors to create a sensor network and process the acquired sensor signals in different domains (time, frequency and modal). The signals picked up by FBG sensors could be interrogated in the same instrument by detecting the wavelength shifts of FBGs. With minimised timing errors for the multi-sensor data acquisitions, it is easy for multiple parameters by different types of FBG sensors to be fused for the functions such as condition information extraction and damage identification. The paper describes multi-parameter measuring principle of FBG and the framework of the proposed system. Multi-parameter dynamical measuring experiments on a hydraulic piping experimental platform have been carried out to validate the system. The system has been used to monitor the clamping looseness of a hydraulic pipe. Experimental results indicate that the proposed system has good potential for multi-parameter dynamical measurement and real-time condition monitoring of industrial hydraulic piping.

2. Multi-parameter dynamical measuring system

Except coating like acrylate, bare FBGs without any other packaged materials or structures can be used directly to measure strain and temperature. Combining elastic sensing elements with different functions to sense and convert measured physical quantities to quantities (like strains) that could be detected by FBGs enables FBGs to measure different physical parameters such as pressure, acceleration, and flow rate, in hydraulic piping systems. A multi-parameter dynamical measuring system is proposed based on an analysis of the FBG multi-parameter measuring principle.

2.1. Multi-Parameter Measurement by FBGs

The central wavelength (λ_B) of the reflected light by an FBG can be defined as [41]:

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

where n_{eff} is the effective refractive index and Λ is the Bragg grating period. The wavelength shift ($\Delta\lambda_B$) of FBG is modulated by the changes of strain and temperature simultaneously, which affect n_{eff} and Λ.

Assuming that temperature remains constant, the wavelength shift of the FBG induced by longitudinal strain change ($\Delta\varepsilon$) can be expressed as:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - p_e)\Delta\varepsilon \tag{2}$$

where p_e is the effective photo-elastic coefficient related to fibre property. According to Equation (2), the relationship between strain and FBG wavelength can be obtained.

$$\Delta\varepsilon = \frac{1}{\lambda_B(1 - p_e)}\Delta\lambda_B = k_\varepsilon \Delta\lambda_B \tag{3}$$

where k_ε is the strain sensitivity of a bare FBG. As the effective photo-elastic coefficient (p_e) of fused silica fibre is approximately 0.22, the strain sensitivity (k_ε) of 1.2 pm/με can be obtained for an FBG with a central wavelength of 1550 nm.

Assuming that strain remains constant, the FBG wavelength shift induced by temperature change (ΔT) can be calculated:

$$\frac{\Delta\lambda_B}{\lambda_B} = (\alpha_f - \xi)\Delta T \tag{4}$$

where α_f and ξ are the thermal expansion coefficient and thermal optical coefficient of fused silica fibre, respectively. The relationship between temperature and FBG wavelength shift can be obtained by rewriting Equation (4).

$$\Delta T = \frac{1}{\lambda_B(\alpha_f - \xi)}\Delta\lambda_B = k_T\Delta\lambda_B \tag{5}$$

where k_T is FBG temperature sensitivity. For an FBG in fused silica fibre with a central wavelength of 1550 nm, its temperature sensitivity is around 10 pm/℃.

Although an FBG is directly sensitive to strain and temperature, it could be used to measure other physical parameters by combining with spring sensing elements with different functions, as shown in Figure 1. FBG sensors adopt spring sensing elements to sense and convert measured quantities (such as pressure, acceleration and flow rate) to the quantities (like strains), which could be detected directly by FBGs. For instance, in order to compensate the temperature cross-sensitivity of FBG, two FBGs (like FBG-3 and FBG-4) can be combined for pressure measurement using a circular metal diaphragm as a spring sensing element [32].

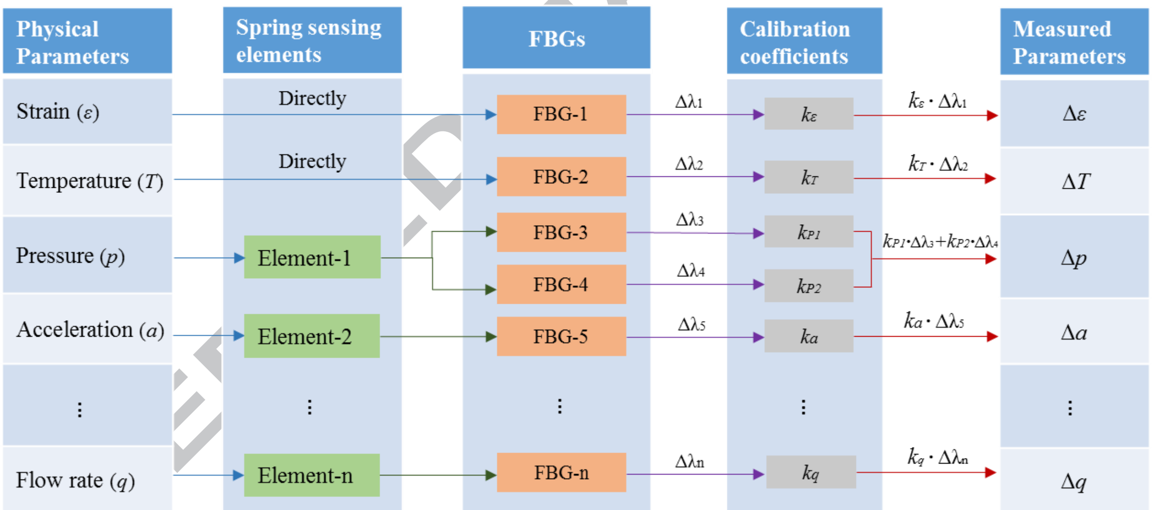


Figure 1. FBG multi-parameter measurement.

As shown in Figure 1, the relationships between the measured multi-parameters and the wavelength shifts of FBGs can be expressed by the following matrix.

$$\begin{bmatrix} \Delta\varepsilon \\ \Delta T \\ \Delta p \\ \Delta a \\ \vdots \\ \Delta q \end{bmatrix} = \begin{bmatrix} k_{\varepsilon} \cdot \Delta\lambda_1 \\ k_T \cdot \Delta\lambda_2 \\ k_{P1} \cdot \Delta\lambda_3 + k_{P2} \cdot \Delta\lambda_4 \\ k_a \cdot \Delta\lambda_5 \\ \vdots \\ \Delta\lambda_n \end{bmatrix} = \begin{bmatrix} k_{\varepsilon} & 0 & 0 & 0 & 0 & \cdots & 0 \\ 0 & k_T & 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & k_{P1} & k_{P2} & 0 & \cdots & 0 \\ 0 & 0 & 0 & 0 & k_a & \cdots & 0 \\ 0 & 0 & 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & 0 & 0 & \cdots & k_q \end{bmatrix} \begin{bmatrix} \Delta\lambda_1 \\ \Delta\lambda_2 \\ \Delta\lambda_3 \\ \Delta\lambda_4 \\ \Delta\lambda_5 \\ \vdots \\ \Delta\lambda_n \end{bmatrix} \tag{6}$$

where $\Delta\varepsilon$ ΔT Δp Δa … Δq are the measured parameters of strain, temperature, pressure, acceleration, …, flow rate, and k_ε k_T k_{P1} k_{P2} k_a … k_n are the related sensitivity coefficients.

As an FBG is directly and simultaneously sensitive to strain and temperature, for pure strain or temperature measurement, compensation is essential to avoid cross-sensitivity. A temperature-measuring FBG could be employed as temperature compensation for a strain-measuring FBG. For example, as shown in Equation (6), the pressure sensor contains multiple FBGs to detect the same parameter (pressure). Due to their multiplexing capabilities such as wavelength division multiplexing, time division multiplexing and space division multiplexing, FBG sensors could readily be used for quasi-distributed measurements in hydraulic piping.

2.2. Multi-Parameter Dynamical Measuring System

For measurements of multiple physical parameters in hydraulic piping systems, FBG sensors with different functions are implemented to detect strain, temperature, pressure, acceleration, flow rate, etc. The optical switch and FBG interrogator are data acquisition devices. Signal analysis includes time domain analysis, frequency domain analysis, modal domain analysis, and condition identification. The signal analysis produces the values of physical parameters (strain, temperature, pressure, acceleration, flow rate, etc.), and modal parameters (frequency, damping ratio, displacement modal shape, strain modal shape, etc.), and real-time condition information on the hydraulic piping system.

The main advantages of the proposed system include: ability to mix and match different sensor types in the same sensor network, simplified data acquisition device and cable management of sensors, minimised timing errors for the acquisitions of different parameters, and easy of combining data from different types of FBG sensors for the functions such as condition monitoring and damage identification.

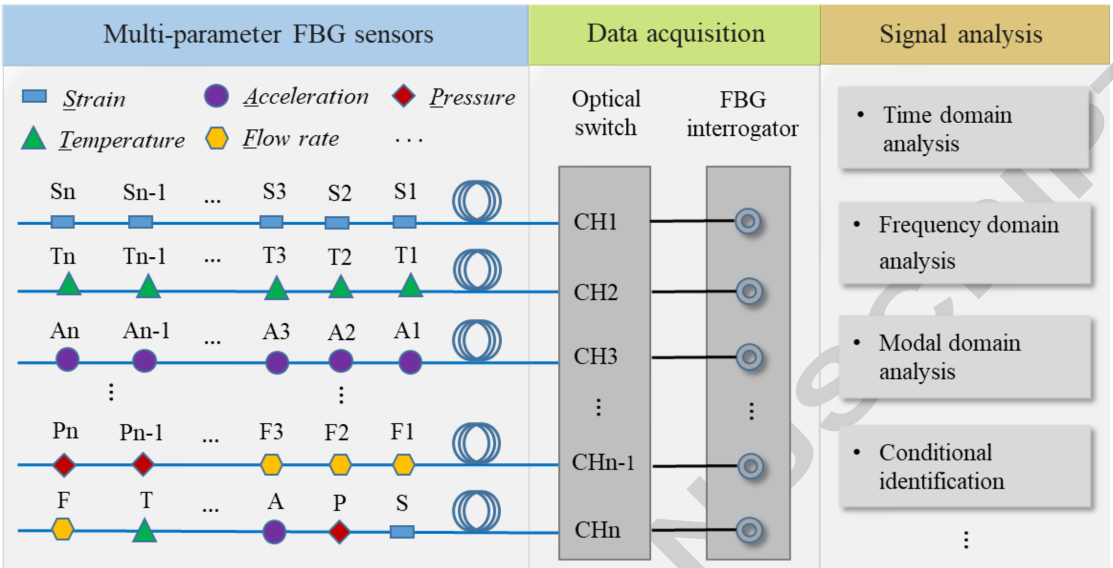


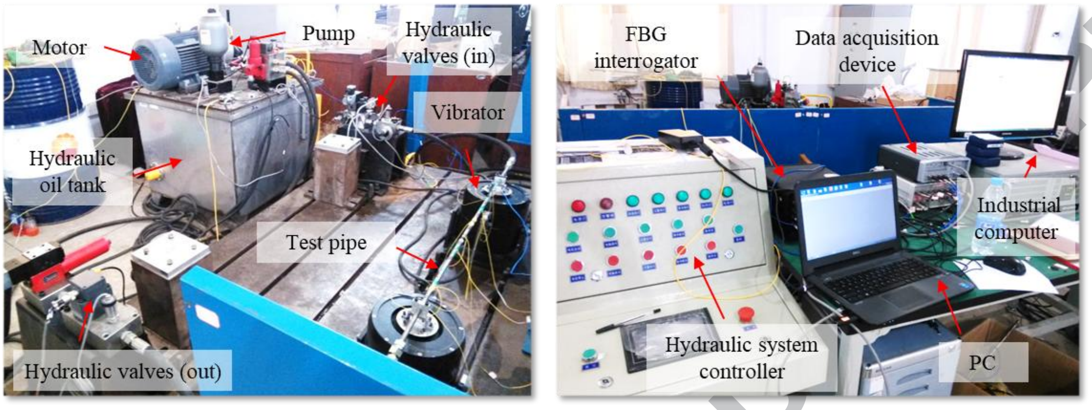
Figure 2. Multi-parameter dynamical measuring system using FBG sensors.

3. Experimental details

To validate the proposed multi-parameter dynamical measuring method and system, experimental investigations on a hydraulic piping test platform were carried out. The platform had twelve FBG sensors (one temperature sensor, nine strain sensors, one pressure sensor and one acceleration sensor) and four reference electrical or piezoelectric sensors (an electric temperature sensor, electric pressure transducer and two piezoelectric accelerometers). The proposed system was preliminarily implemented to monitor the clamp looseness of the hydraulic pipe.

3.1. Experiment Setup

As illustrated in Figure 3(a), the main components of the setup are a motor, a hydraulic oil tank, a pump, hydraulic valves (in), two vibrators, hydraulic valves (out), and a test pipe. The control and data acquisition devices including the hydraulic system controller, FBG interrogator, data acquisition devices, industrial computer, and PC, are shown in Figure 3(b). A hydraulic system with valves was adopted to control pressure and flow rate of fluid in the pipe. A vibrator with power amplifier was applied to excite the test pipe with a known load. An FBG interrogator with a maximum sampling frequency of 4 kHz was used to monitor the wavelength shifts of all FBG sensors for the measurement of strain, temperature, pressure, and acceleration. Data from the electric sensors and piezoelectric sensors as reference sensors was obtained by the data acquisition device and industrial computer.



(a) (b)

Figure 3. Experiment setup (a) components in the hydraulic system, (b) control and data acquisition devices.

3.2. Installation of Sensors

Figure 4 shows the installation of the sensors and transducers used in the experiments. An FBG temperature sensor and an electric temperature sensor were fitted inside in the hydraulic oil tank to monitor the temperature change of oil, as shown in Figure 4(a). An FBG acceleration sensor (OS7100, Micron Optics Inc.) and a piezoelectric accelerometer (353B18, PCB Piezotronics Inc.) were placed on the valves of the tank to measure vibration. Figure 4(b) shows the FBG pressure sensor and electric pressure transducer (PSM300, Wuhan Aviation Sensing Tech. Ltd.) on hydraulic valves (out) to detect the dynamical changes of oil pressure in the test pipe.

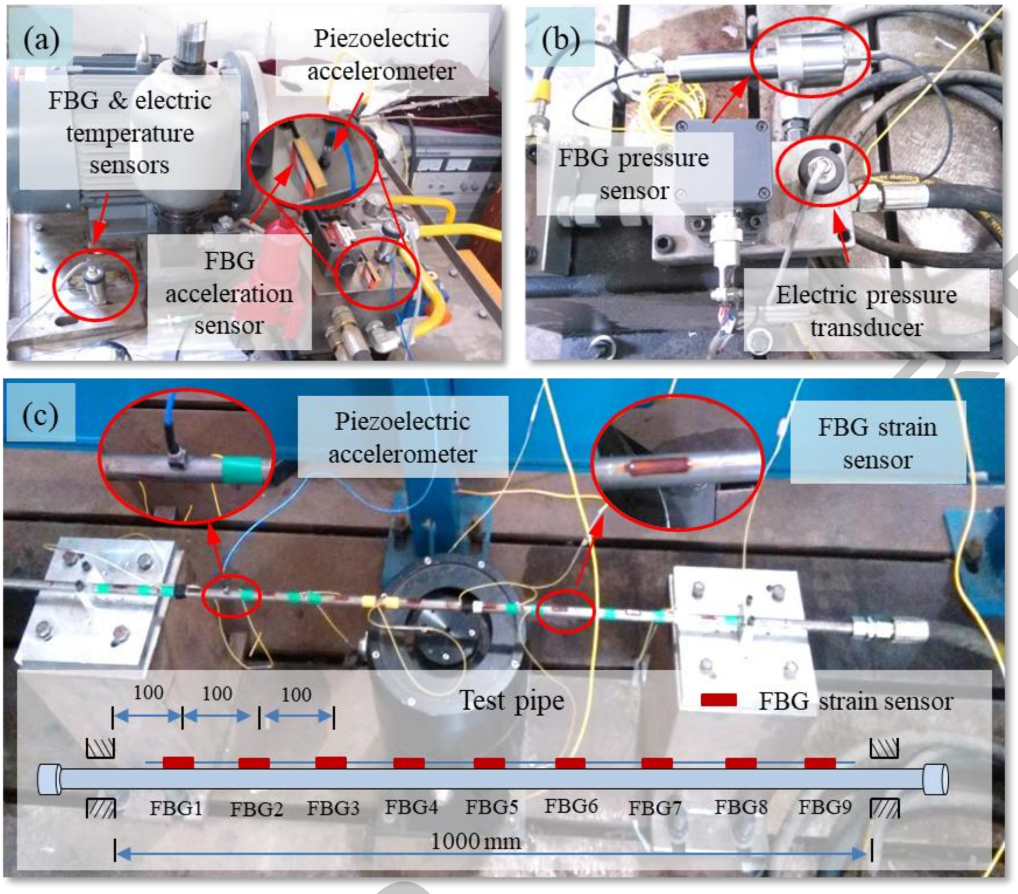


Figure 4. Installation of sensors (a) temperature sensors and acceleration sensors, (b) pressure sensors, (c) accelerometer and strain sensors.

As illustrated in Figure 4(c), the test pipe filled with hydraulic oil was fixed at two ends, and the length of the pipe between the two fixed points was 1000 mm. A piezoelectric accelerometer was installed on the test pipe to measure its vibration, and nine FBG strain sensors (bare FBGs with acrylate coating, WUTOS Co. Ltd.) were mounted on the pipe at intervals of 100 mm. Although more FBG strain sensors will increase the precision of the modal parameter measurements, considering practical installation issue, nine FBG strain sensors were implemented to measure dynamical strain responses.

The proposed system was preliminarily employed to monitor the clamp loosening of the hydraulic pipe under operating conditions. As shown in Figure 5, the pressure of the hydraulic oil inside the test pipe is 3.0 MPa with a flow rate of 199 ml/s. Metal clamps were employed to fix the test pipe at two ends. The clamp loosening may occur due to vibration fatigue. The FBG strain sensor installed on the test pipe was adopted to detect the dynamical strain response in real time.

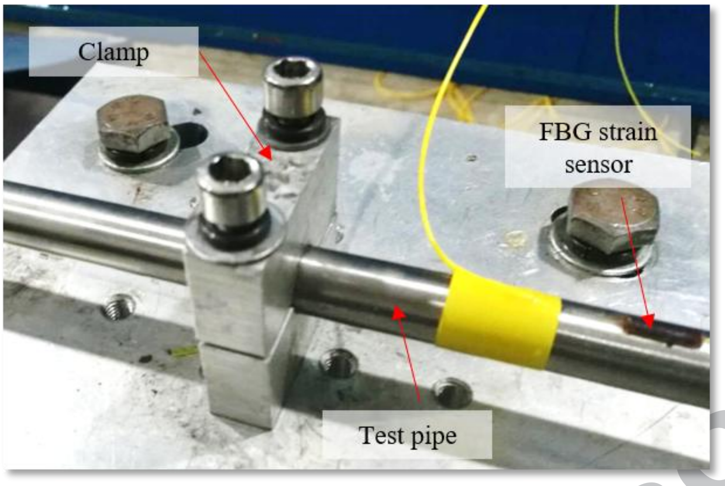


Figure 5. Clamp looseness monitoring using the proposed system.

4. Results and discussion

The experimental data acquired by FBG sensors and the reference electrical or piezoelectric sensors were analysed in the time domain and modal domains, and multiple physical parameters of the hydraulic piping system were obtained.

4.1. Time Domain

The temperature changes of the oil in the tank are shown in Figure 6(a), which were measured by FBG temperature sensor and the electric temperature sensor at the same time. Figure 6(b) illustrates the results of the changes of hydraulic oil pressure in the test pipe, which were simultaneously recorded by an FBG pressure sensor and an electric pressure transducer. The maximum differences of the measured temperature and pressure are approximately 0.7 ℃ and 0.15 MPa, respectively. It could be seen that the results obtained by the FBG sensors are in good agreement with those acquired by the reference electric sensors, and have a better signal-to-noise ratio. Figure 6(c) and Figure 6(d) show the accelerations detected by the FBG acceleration sensor and the piezoelectric accelerometer respectively, which were installed close to each other on the oil tank as shown in Figure 4(a). The approximated amplitude fluctuation ranges of FBG acceleration sensors and piezoelectric accelerometer are respectively -0.2 g to 0.2 g and -0.16 g to 0.19 g within 1.0 s, excluding some maximum values and minimum values. The difference between the ranges is approximately 0.05 g.

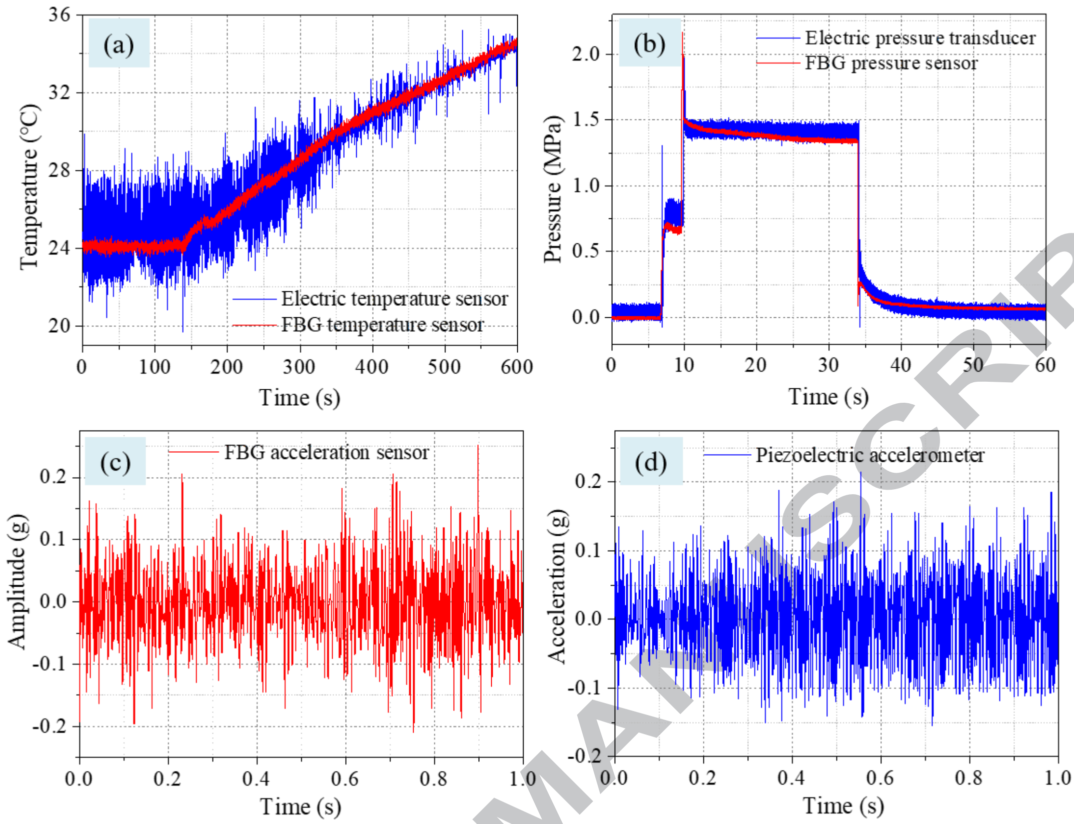


Figure 6. Experimental results (a) temperature, (b) pressure, (c) acceleration response by FBG sensor, (d) acceleration response by piezoelectric accelerometer.

The hydraulic oil in the test pipe was static with a pressure of zero MPa. The test pipe was excited by an impact force induced by a hammer with a force sensor inside. Figure 7 illustrates the dynamical strain responses measured by nine FBG strain sensors mounted on the surface of the test pipe (as shown in Figure 4(c)). The sampling frequency of the FBG sensors was 2 kHz. As temperature changes are small and slow, their effects on the wavelength shifts of FBG strain sensors were ignored for the measurement of dynamical strain responses over a short period (2.5 s) as shown in Figure 7.

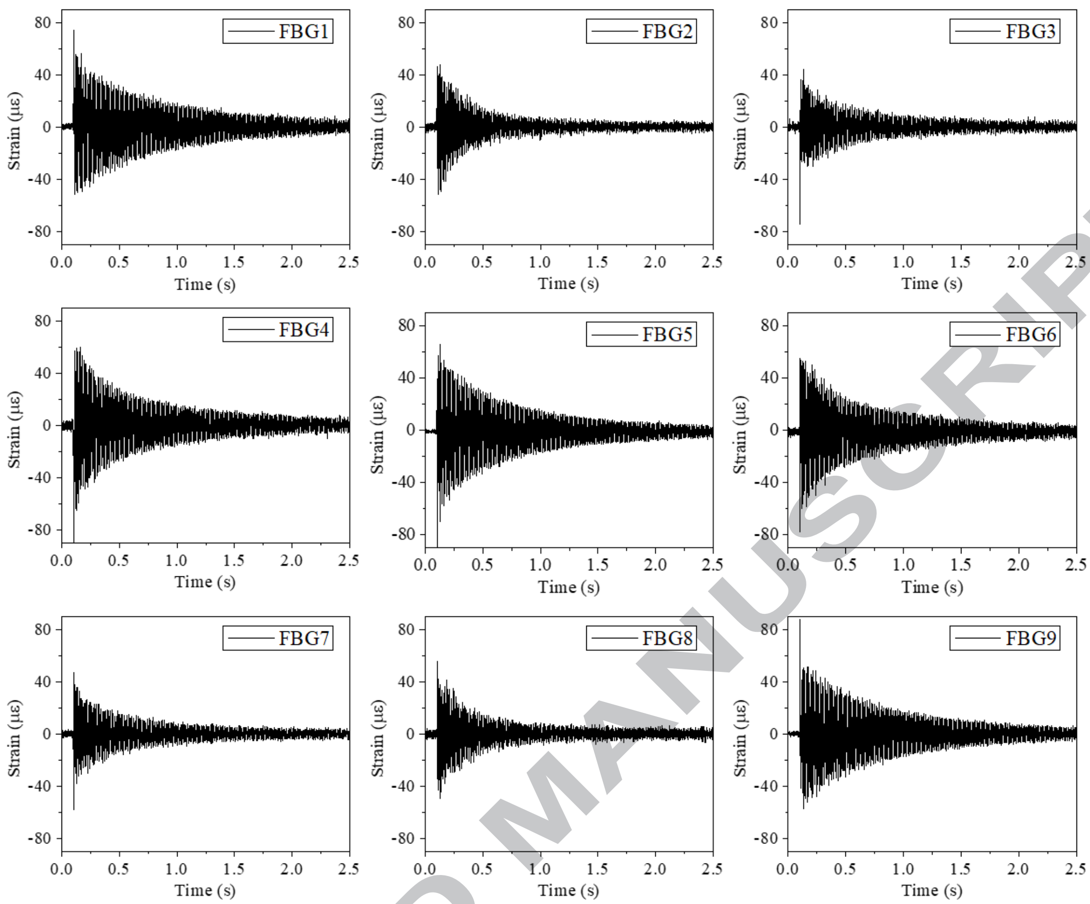
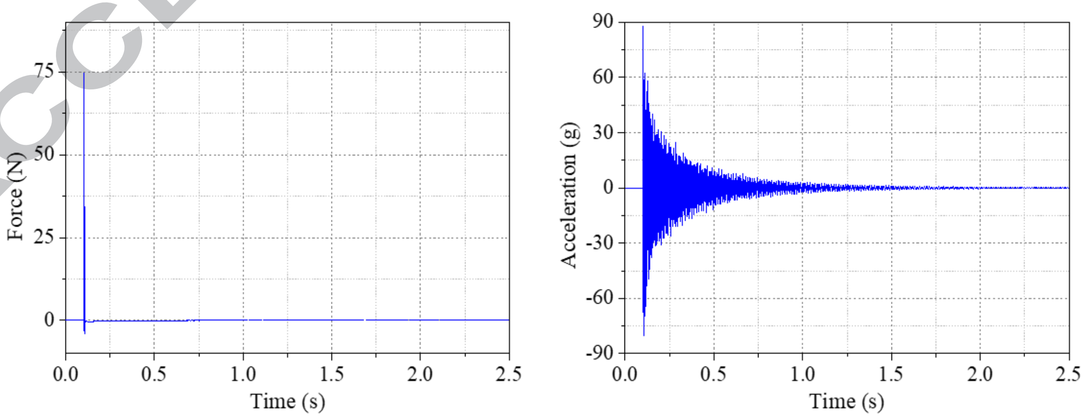


Figure 7. Dynamical strain responses measured by FBG strain sensors.

Figure 8(a) shows the impact force measured by the force sensor embedded in the hammer and the curve in Figure 8(b) is the acceleration response detected by the piezoelectric accelerometer installed on the test pipe (as shown in Figure 4(c)).



(a) (b)

Figure 8. (a) Impact force, (b) acceleration response measured by piezoelectric accelerometer.

4.2. Frequency Domain

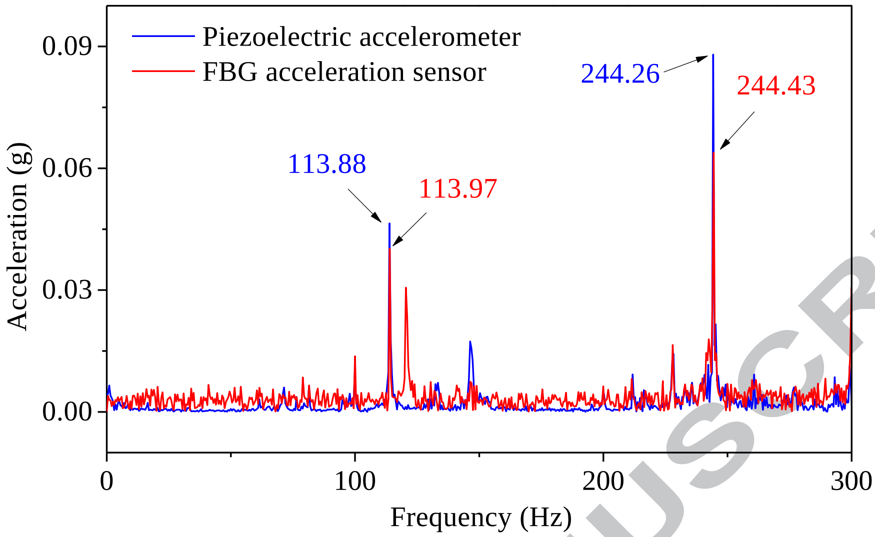


Figure 9. Frequency responses of acceleration.

The frequency response of the acceleration signals in Figure 5(c) and Figure 5(d) obtained by Fast Fourier Transform (FFT) are shown in Figure 9. As the FBG acceleration sensor (113.97 Hz and 244.43 Hz) and the piezoelectric accelerometer (113.88 Hz and 244.26 Hz) were mounted near to each other on that tank, they captured the same main vibration frequency components. The frequency spectrum of the piezoelectric accelerometer is clearer than that of the FBG acceleration sensor as the acceleration sensitivity of the piezoelectric accelerometer is higher.

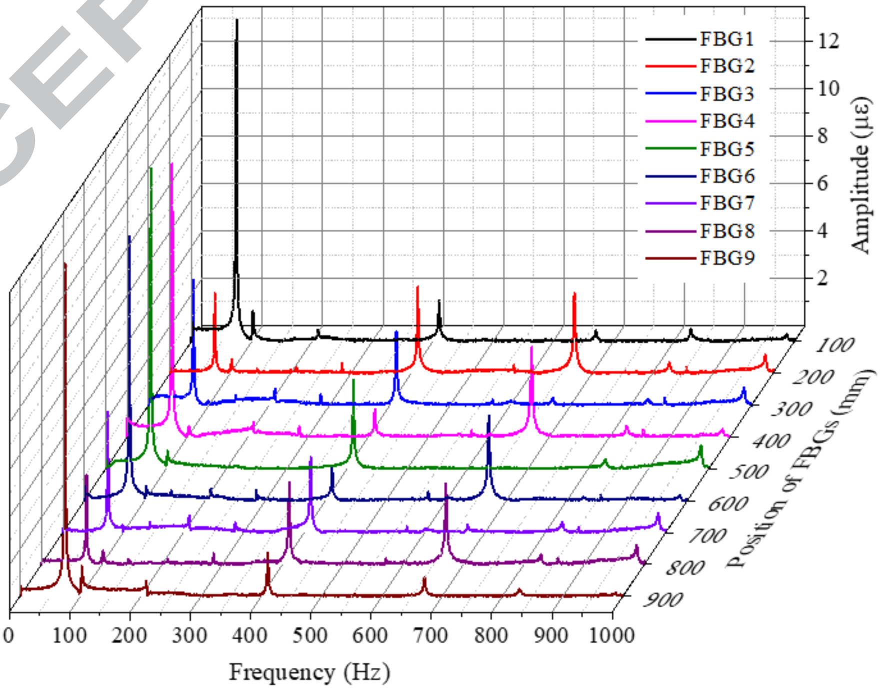
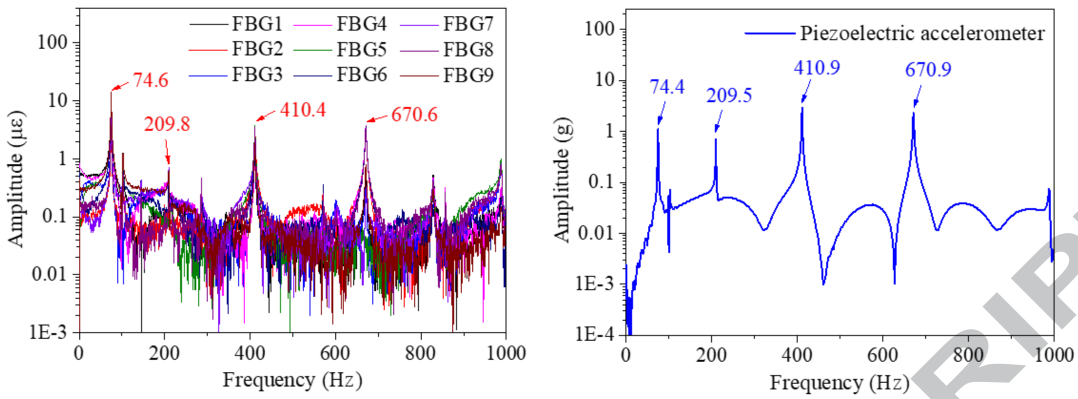


Figure 10. Frequency spectra of nine FBG strain sensors on the test pipe.



(a) (b)

Figure 11. Natural frequencies of the test pipe (a) FBG strain sensors, (b) piezoelectric accelerometer on the test pipe.

Figure 10 depicts the frequency spectra of the dynamical strain responses detected by the nine FBG strain sensors in Figure 7. As shown in Figure 11(a) and Figure 11(b), the first four natural frequencies of the test pipe obtained by the piezoelectric accelerometer were 74.6 Hz, 209.8 Hz, 410.4 Hz and 670.6 Hz, closely corresponding to those picked up by the FBG sensors (74.4 Hz, 209.5 Hz, 410.9 Hz, and 670.9 Hz).

4.3. Modal Domain

Table 1. Damping ratio and natural frequency of the test pipe.

Mode number	Damping ratio (%)	Natural frequency (Hz)		
	FBG sensors	FBG sensors	Accelerometer	Difference (%)
1	0.665	74.6	74.4	0.27
2	0.305	209.8	209.5	0.14
3	0.145	410.4	410.9	0.12
4	0.195	670.6	670.9	0.03

The frequency domain results of the dynamical strain response obtained by the nine FBG strain sensors and the excitation force measured by the force sensor in the hammer could be used to calculate Strain Frequency Response Functions (SFRFs). Then the modal parameters of the test pipe including natural frequency, damping ratio, and strain mode shape, can be estimated from the SFRFs [48]. The results of the first four mode damping ratios and natural frequencies of the test pipe are shown in Table 1. The differences between the natural frequencies measured by the FBG strain sensors and the reference piezoelectric accelerometer are small (0.27 %, 0.14 %, 0.12 % and 0.03 %), which indicates that the FBG sensors obtained accurate results.

Figure 12 illustrates the normalised strain mode shapes of the test pipe along its length. According to the strain mode shapes, the strain distribution of the pipe could be determined, which is useful for condition monitoring and damage identification in hydraulic piping systems.

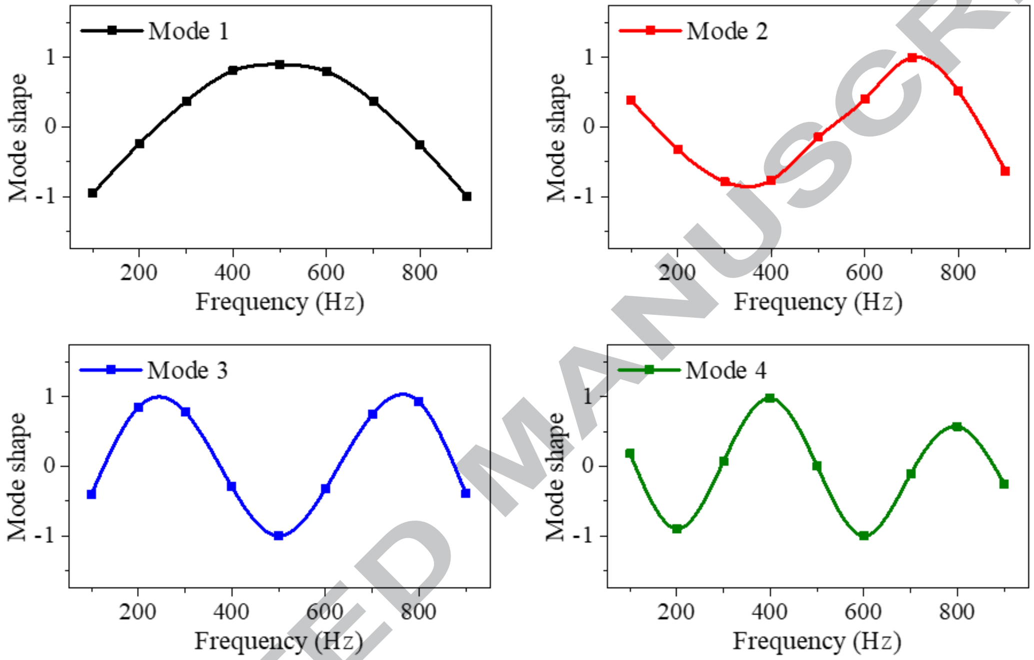


Figure 12. The first four normalized strain mode shapes of the test pipe.

Using the frequency domain results of the dynamical strain response obtained by the nine FBG strain sensors and the excitation force measured by the force sensor in the hammer, Strain Frequency Response Functions (SFRFs) can be calculated. Then the modal parameters of the test pipe including natural frequency, damping ratio, and strain mode shape, can be estimated from the SFRFs [48]. The results of the first four mode damping ratios and natural frequencies of the test pipe are shown in Table 1. The small differences between the natural frequencies measured by the FBG sensors and the reference accelerometer indicates that the results obtained by the FBG sensors are accurate.

4.4. Clamp Looseness Monitoring

FBG strain sensor was employed to monitor the dynamical strain responses of the test pipe under operating conditions. Impact forces were applied on the test pipe before and after clamp looseness occurred at one supporting end, as shown in Figure 5. Figure 13 illustrates the changes of the first three mode natural frequencies of the test pipe detected by the FBG strain sensor. The change of the first mode natural frequency of the test pipe is 0.2 Hz. The second and third mode natural frequencies of the test pipe reduce by 9.1 Hz (4.8 %) and 20.3 Hz (5.4 %) after the clamp loosed, respectively. The natural frequency decreases of the test pipe was caused by the constraint stiffness change due to the clamp looseness. Therefore, the clamp looseness of hydraulic pipes can be monitored by detecting the changes of natural frequencies using the proposed FBG dynamic measurement system. Preliminary trials show that the proposed system is feasible for condition monitoring of hydraulic pipes.

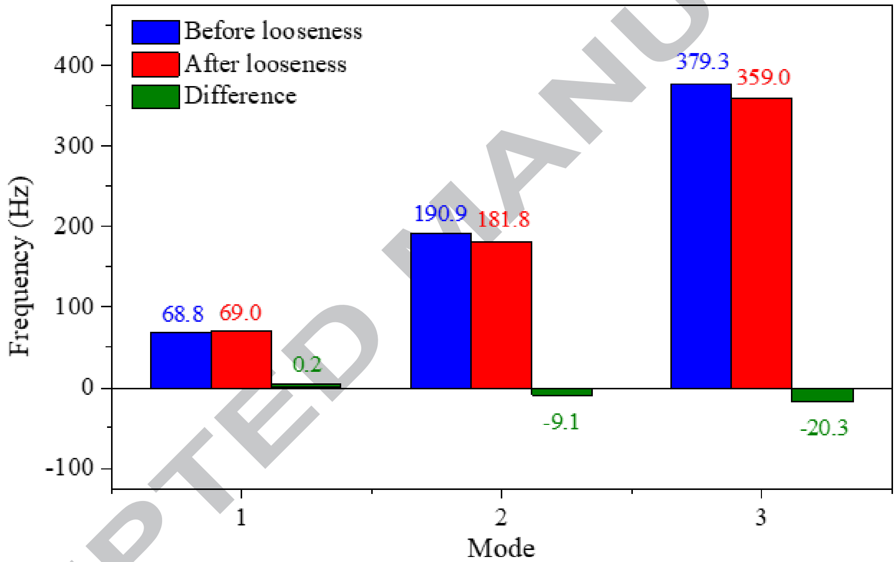


Figure 13. Changes of the first three mode natural frequencies of the test pipe.

4.5. Future Work

Future work will focus on the development of FBG sensors for flow rate measurement, and investigation of multi-sensor data fusion, damage identification, and condition information extraction methods. A new kind of practical FBG sensor for flow rate measurement with high precision and high reliability will be developed and integrated in the proposed multi-parameter dynamical measuring system. Combining data measured by multiple FBG sensors for the same physical process (multi-sensor data fusion) can improve the accuracy and robustness of damage identification and condition assessment of hydraulic piping.

5. Conclusions

Dynamical measurement of multiple physical parameters is necessary to obtain information to prevent fatigue failures in hydraulic piping system. Although FBG sensors have already been used for monitoring individual parameters of a pipeline, there is not a convenient platform for simultaneous measurement of multiple parameters at many different locations and in a dynamic environment. Based on previous research on FBG sensors and signal processing methods, a new dynamic measurement system has been implemented to detect multiple dynamic parameters for industrial hydraulic piping. This paper has presented the system framework and its multi-parameter measurement principle. The proposed system can accommodate numerous FBG sensors to create a sensor network for distributed measurement. It can process the acquired sensor signals in different domains (time, frequency and modal) to extract information on the condition of hydraulic piping.

Multi-parameter dynamical measuring experiments in a hydraulic piping experimental platform were carried out to demonstrate the presented system. The results of comparison experiments with electrical and piezoelectric sensors indicate that the new system is a good solution to the problem of multi-parameter dynamical measurement in hydraulic piping thanks to its integrated nature and its simplicity as all the sensors used are of the same type. The proposed system was implemented to monitor the clamp looseness of the hydraulic pipe under operating conditions. Preliminary trials show that the proposed system is feasible for real-time condition monitoring of industrial hydraulic pipes.

Acknowledgments

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Table 1. Damping ratio and natural frequency of the test pipe.

Mode number	Damping ratio (%)	Natural frequency (Hz)		
	FBG sensors	FBG sensors	Accelerometer	Difference (%)
1	0.665	74.6	74.4	0.27
2	0.305	209.8	209.5	0.14
3	0.145	410.4	410.9	0.12
4	0.195	670.6	670.9	0.03

Highlights

- A multi-parameter dynamical measuring system using FBG sensors was proposed.
- System framework and multi-parameter measuring principle were described.
- Experiments on a hydraulic piping platform were conducted to validate the system.
- Results obtained by FBG sensors agreed well with those by the reference sensors.